VIAVI Solutions

White Paper

Transmission of Engineered Diffusers

Engineered Diffusers® continue to set new standards for light shaping, now with wide field-of-view diffusers from VIAVI Solutions Inc. To accurately characterize the transmission performance of such wide-angle diffusers, careful attention must be paid to the measurement technique. This white paper provides background and methods for the accurate characterization of transmission of Engineered Diffusers.

Optical diffusers are often used to spread and homogenize the light distribution from various types of light sources. Our white paper titled *How to use Engineered Diffusers*, provides illustrative illumination configurations that benefit from optical diffusers. As noted in this paper our diffusers enable efficient light management with sharp spatial cutoff configurations. Standard diffusers such as ground glass or holographic diffusers have limited angular ranges that are circular or elliptical, and their intensity profiles are generally Gaussian or Gaussian-like. Opal glass provides a very wide angle, Lambertian distribution, but its efficiency is very low. Several years ago, VIAVI Solutions, introduced the Engineered Diffuser, a new type of diffuser capable of controlling the light distribution, both the intensity profile and the two-dimensional angular range of the distribution. The Engineered Diffuser is a refractive diffuser with microstructures much larger than a wavelength that are used to control the light distribution.

A goal in the design of the diffuser is to make the most efficient use of the light that is available, putting the light where it is needed with as little waste as possible. Thus, we want the diffuser to be highly transmissive with minimal loss. Opal glass is a volume diffuser, and is therefore very inefficient, transmitting only about 30% to 35% of the incident light over the visible to NIR spectral range. Ground glass is slightly more efficient when the scatter angles are low, about 50% for a 10° FWHM diffuser, and 41% for a 25° FWHM. The transmission drops to 23% for a 60° FWHM diffuser. Holographic diffusers are much more efficient, with transmission in the upper 80 and low 90 percent range. But fine control of the light distribution is difficult. Engineered Diffusers offer both excellent light control as well as high efficiency. It's important to understand how the light scattering capabilities of the diffuser impact the transmission of the diffuser, especially for the high angle designs.

Transmission through an Engineered Diffuser is governed by several factors: material absorption, slope angle of the micro-structured surface, diffuser index – which is tied to surface slope angles – and substrate properties. Engineered Diffusers are fabricated in several formats including replicated polymers on glass and patterns etched into substrates. Polymer-on-glass (PoG) is a replication process where the diffuser is transferred from a master tool into a polymer material on a glass substrate. Etched diffusers are created from either a polymer or resist material on a substrate that is then etched through a reactive ion etching process transferring the surface profile of the diffuser into the substrate material. The substrate material becomes the diffuser. Embossed diffusers are created by stamping a master tool into a material such as polycarbonate to form a diffuser surface on one side of a homogeneous material. These are demonstrated in Figure 1 below. Other processes are possible for creating the diffuser, but all share the same principles for transmission.

Polymer on Glass Diffuser

Etched or Embossed Diffuser

Figure 1. Types of diffuser technologies

Material absorption is a property of the chemical structure of the material used in creating the diffuser, and of the diffuser substrate. For the most part it is independent of the nature of the diffuser, i.e., diffuser scatter angle and surface slope angles. It is a function of the thickness of the absorbing material and length of the light path traveled through the material. For the materials used in our PoG diffusers, the absorption is insignificant over the wavelength range of 400 nm to 2000 nm. Other materials will have different wavelength ranges where absorption may become a more significant factor in determining diffuser transmission. But for the analysis described here, no absorption will be considered, though it may play a role in the actual transmission of the diffuser at the wavelength being used by the customer. The measurement technique that will be described below is applicable to any diffuser material and illumination wavelength.

Refractive Index and Wavelength

Engineered Diffusers are refractive structures. They rely on refraction to control and manipulate the transmitted light. As such they depend on the index of refraction of the materials used to make them. Typical materials used for the diffusers and substrates have an index that decreases with increasing wavelength. Figure 2 shows the refractive index of two theoretical polymer materials over the wavelength range of 400 nm to 2000 nm, one with a high index and the other a low index. The behavior of decreasing index with wavelength is typical of the optical materials used to make the diffusers whether they are polymers, etched glasses or embossed plastics.

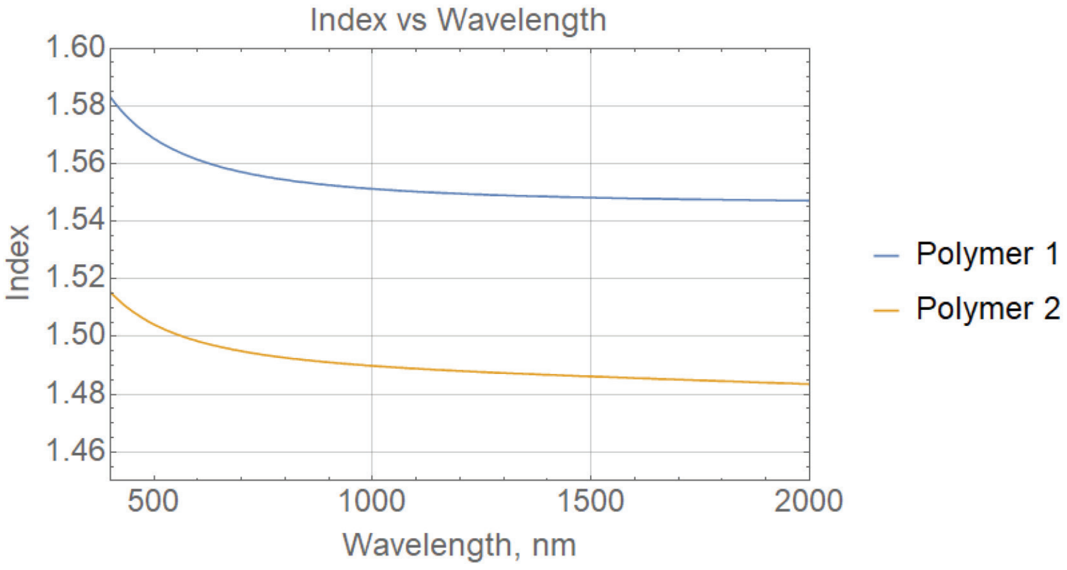


Figure 2. Index of refraction of two polymers versus wavelength.

Angles of Incidence

The surface of an engineered diffuser contains thousands of tiny microstructures whose size and shape are used to manipulate the incident light to create a desired illumination pattern. These microstructures can be concave, convex or a combination of both. The surface slopes of these microstructures refract the incident light directing it in a predetermined fashion. Since these are refractive structures, the amount of refraction depends on both the surface slope and the index, and since the index is a function of wavelength, the amount of refraction will also be a function of the wavelength. A longer wavelength, having a lower index in the diffuser material, will experience less refraction than a shorter wavelength, and therefore the diffuser will scatter longer wavelength light to smaller scatter angles than it will for shorter wavelengths.

This is illustrated in Figure 3 which shows a microstructure surface relief on the input side of a diffuser. Both red light and blue light illuminate the diffuser. In the figure a single light ray for each color is shown striking the same surface point on the diffuser. Since the index for blue is higher than for red, the blue light is refracted more than the red. As the rays travel through the diffuser they separate and strike the output surface at slightly different angles. They then emerge from the substrate at different angles, red at a shallower angle and blue at a steeper angle. Thus, the same diffuser illuminated at different wavelengths will have slightly different divergence angles: narrower for red, and wider for blue. However, this difference is usually quite small. For example, suppose we have a material with an index of 1.5645 at 450 nm and 1.5489 at 650 nm. If we design a diffuser with a 120° field of view (FOV) (±60° divergence) for a wavelength of 450 nm, then at 650 nm the FOV will be 115.88° (±57.94°). This is about a 3.4% change in the FOV for this wavelength difference.

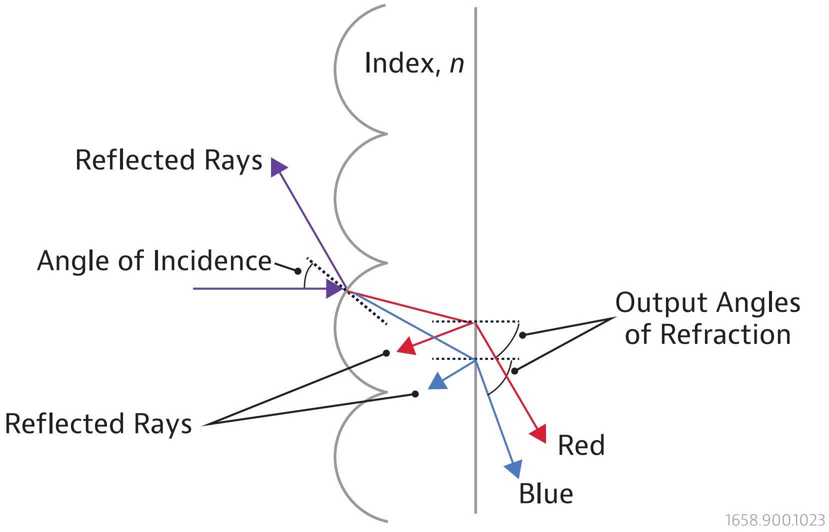


Figure 3 Refraction of red and blue rays by a microstructure surface.

Fresnel Reflection and Transmission Coefficients

We now consider how the transmission through the diffuser is affected by the slope of the surface, or rather, the incident angle of the light on the surface, both at the structured or input side and the substrate or output side, as well as any internal surface interfaces of the diffuser. The light transmitted through these surfaces is governed by the Fresnel reflection and transmission coefficients. The reflection, *R*, and transmission, *T*, coefficients for *S* and *P* polarization for a single-surface interface are

$$R_S = \left\{ \frac{n_1 \cos\theta_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2}}{n_1 \cos\theta_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2}} \right\}^2 \qquad T_S = \left\{ \frac{4 n_1 n_2 \cos\theta_i \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2}}{n_1 \cos\theta_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2}} \right\}^2$$

$$R_P = \left\{ \frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2} - n_2 \cos\theta_i}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2} + n_2 \cos\theta_i} \right\}^2 \qquad T_P = \left\{ \frac{4 n_1 n_2 \cos\theta_i \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2}}{n_2 \cos\theta_i + n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2}} \right\}^2,$$

where the light travels from the material with index n_1 into the material with index n_2. For unpolarized light the coefficients are the average of the *S* and *P* equations. *P* designates polarization parallel to the plane of incidence and *S* designates polarization perpendicular to the plane of incidence. For non-absorbing materials we have $R+T=1$ in both cases, as expected.

A plot of the transmission coefficients for *S*, *P* and unpolarized light is shown in Figure 4 for light entering a material of index 1.5188 from air. These are single-surface plots. Note that the average transmission remains relatively constant for incident angles up to about 50°. After 70° it falls off quite rapidly.

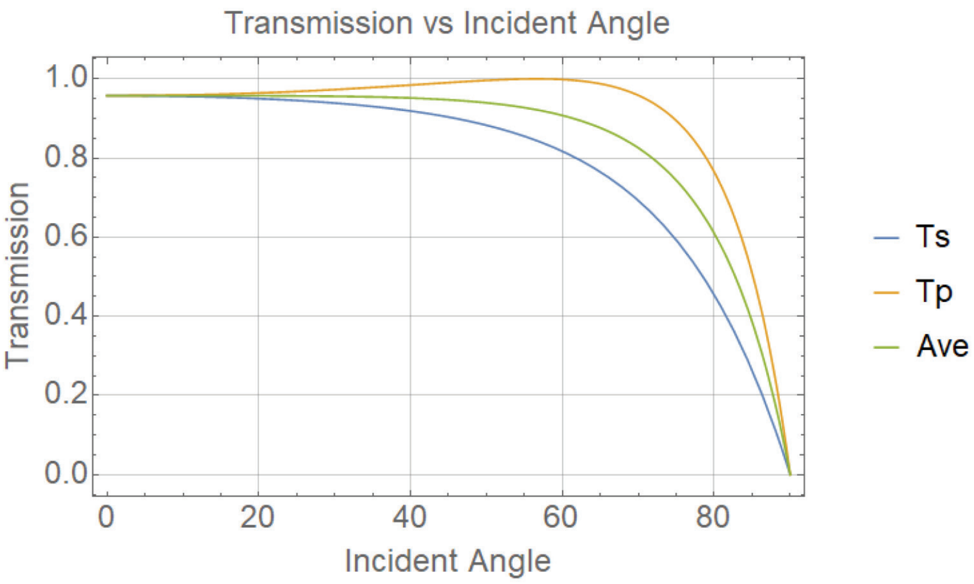


Figure 4. Fresnel transmission coefficient for *S* and *P* polarizations and their average.

So, while a beam of light may be at normal incidence to the diffuser as a whole, there can be large incidence angles on the individual micro-structures that makeup the diffuser surface. Thus, a wide-angle diffuser will have a lower transmission than a narrow angle diffuser since there will be areas of the microstructure surface with steeper slopes for the wide-angle diffuser than for the narrow-angle diffuser. And depending on the shape of the micro-structures used to distribute the light, there may be larger portions of the surface sloped at steep angles for some diffuser designs than for others even if the FOV is the same. For example, a diffuser with a bat-wing intensity profile will have a larger portion of the micro-structure surface sloped at steep angles in order to send more of the light at wide angles compared to a diffuser with a uniform or flat-top intensity profile, even with the same FOV. Therefore, we expect that the bat-wing diffuser will have a lower transmission than the uniform flat-top diffuser.

In Figure 5 we show a comparison between the intensity profiles of a flat top diffuser and a bat-wing diffuser. Bat-wing diffusers are useful for obtaining uniform irradiance on a planar surface. For a discussion on the difference between intensity and irradiance see our white paper titled *Engineered Diffusers – Intensity vs Irradiance*.

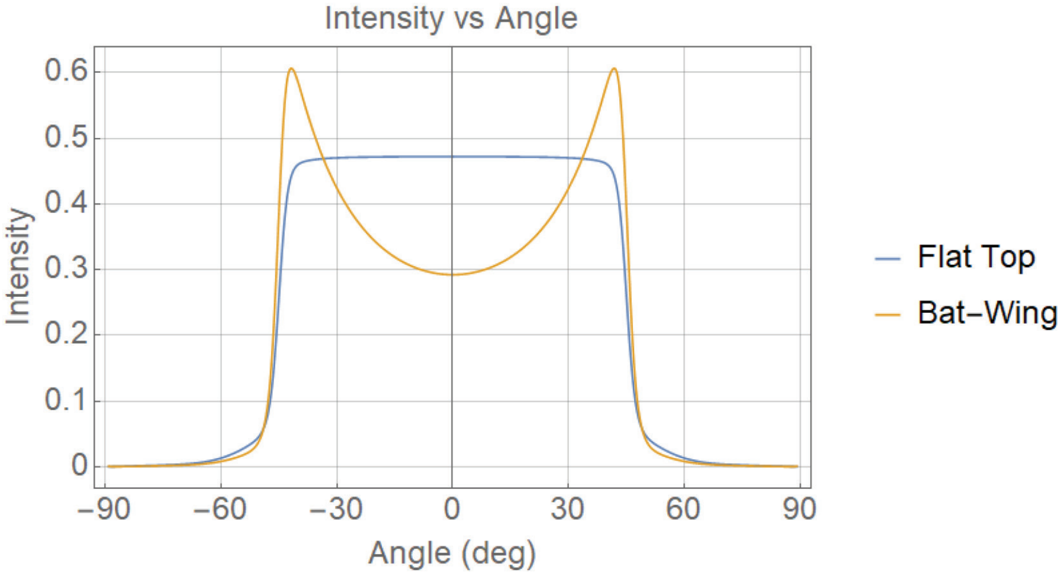


Figure 5. Intensity profiles of flat top and bat-wing diffusers

Transmission will also be lower for higher index materials. Shown in Figure 6 is a plot of the average transmission coefficient from Equation (1) as a function of the material index, n_2, for light traveling from air into the material, for incident angles of 30, 45 and 60 degrees. As the index changes from 1.40 to 1.70, the transmission for each incident angle falls by about 10%. The reflectivity will show a corresponding increase in order to maintain conservation of energy as stated by $R+T=1$.

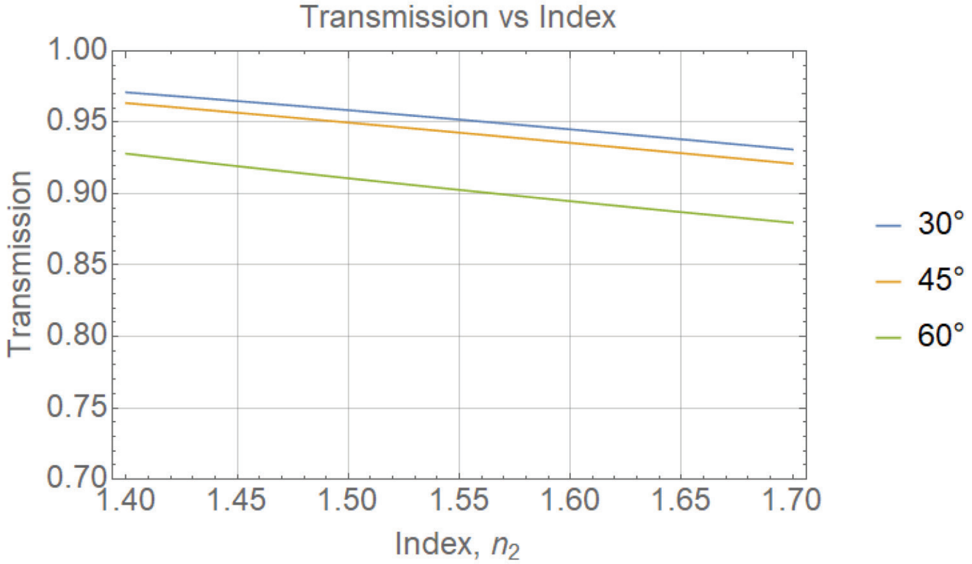


Figure 6. Transmission as a function of index, n_2, for three incident angles.

Referring to Figure 3 for the transmission difference between red (longer) and blue (shorter) wavelengths, we have three effects occurring that influence the transmission of the diffuser. At the input surface we have the same angle of incidence, but the longer wavelength has a lower index and therefore a higher transmission. At the output surface, not only is the index lower for red, but the incident angle at the substrate/air interface is also lower. Both contribute to a higher transmission for red versus blue. These three factors combine to give a higher transmission for longer wavelengths than for shorter wavelengths for any given diffuser design.

Transmission Measurements

Measuring the transmission of a diffuser is done using an integrating sphere, a measurement device designed to capture all the light transmitted through a sample from a known light source. The interior of the sphere is coated with a highly reflective, Lambertian scattering material. A reflectivity of 99% is typical over the visible spectrum. At least two ports are needed, one for the detector and one for the source and diffuser. The basic principle for measuring the transmission of a diffuser is to first measure the incident light source power by allowing the light to enter the open port on the sphere. The light bounces around the interior surface of the sphere and eventually makes its way to the detector and a measurement is recorded. Then the diffuser is placed over the open port with the same illumination source and a second power measurement is taken. The ratio of these two measurements would be the transmission of the diffuser. However, other factors must be considered. First, sufficient baffling must be in place in the interior of the sphere to prevent direct source light from hitting the detector. Baffling must also be present to prevent the first strike light from the source hitting the detector. The first strike light is light from the source that hits the opposite side of the inside of the sphere. There should be sufficient baffling inside the sphere to prevent a direct line of sight of this point to the detector. Second, the baffling must also prevent direct diffuser light from hitting the detector. The ideal configuration of the sphere forces the light from either the source or the diffuser to bounce around several times before reaching the detector. Another issue to consider is when measuring the diffuser, some of the light bouncing around inside the sphere will hit the diffuser and be reflected back into the sphere. This light needs to be discounted since it does not come from a direct transmission through the diffuser. Thus, multiple measurements with and without the diffuser must be made to get an accurate calculation of the diffuser transmission.

A standard integrating sphere, with a baffle between the entrance port and detector port, was determined to be insufficient for these measurements. It reported erroneously high transmission values as it could not be configured to discount the light reflected from the diffuser. Nor could it be configured to shield sufficiently the detector from the wide range of diffuser angles needed to be measured, diffuser angles ranging from 5 to 10° FOV up to diffusers with greater than 120° FOV.

VIAVI obtained two integrating spheres from Labsphere, Inc of North Sutton, NH. Expert guidance from Labsphere provided us with the measurement technique to accurately measure the transmission of our engineered diffusers. An 8″ sphere is configured with appropriate baffling for measuring very wide-angle diffusers, those with a FOV greater than 100°. The sphere has sufficient baffling to shield the detector from any first strike of the illumination source and any direct light from the diffuser. A smaller four-inch sphere is an LPM-040 used for laser power measurements, but appropriate for measuring diffusers with a FOV up to 100°. It was the recommendation of Labsphere engineers to use a two-sphere approach to measure the full angle range of diffusers that Viavi offers.

With each sphere, a series of measurements is taken as shown in Figure 7. This figure depicts the 8″ sphere, but the measurement technique is the same for both 4″ and 8″. We use a collimated laser source so as not to alter the divergence of the diffuser.

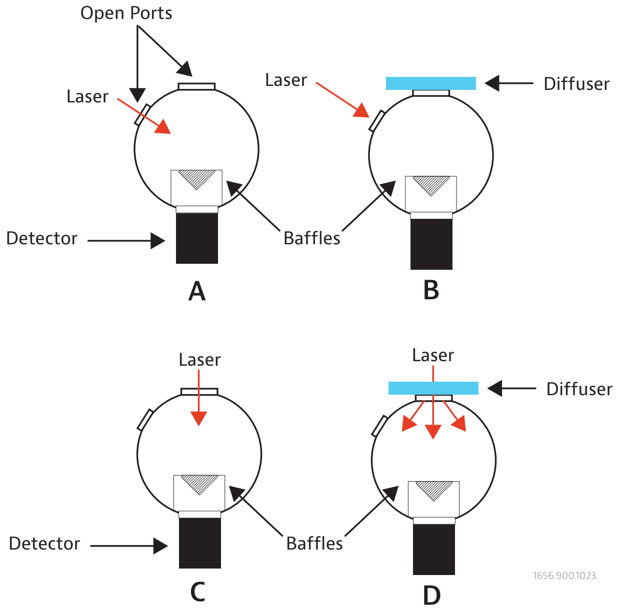


Figure 7. Transmission measurement configurations.

The process for measuring the diffuser transmission is as follows:

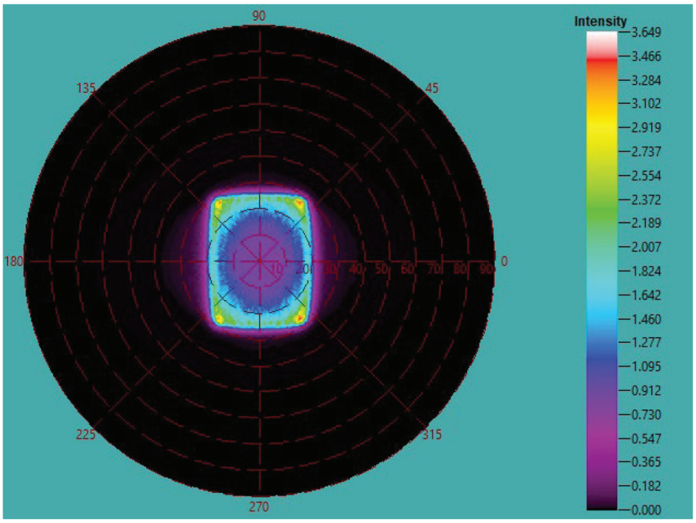
1. The first measurement is taken of the laser power through the side port shown in configuration A with both ports open. This is P_A.
2. Next, the diffuser is placed over the open top port with the laser entering the side port, configuration B. This obtains a measurement of the reflectivity of the diffuser at all angles of incidence. This is P_B, and will be equal to or greater than P_A.
3. The laser is moved to the top port with the side port left open, configuration C. This is power, P_C.
4. Lastly, the diffuser is placed over the top port and a measurement P_D is taken, configuration D. If the laser is polarized, then the diffuser is rotated 90 degrees and a second measurement is taken. The average of these two measurements is used for P_D.

The transmission of the diffuser is calculated as:

$$T = \frac{P_D}{P_C\left(\frac{P_B}{P_A}\right)} 100\%$$

is a reduction factor to account for the light reflected off the diffuser when taking measurement P_D.

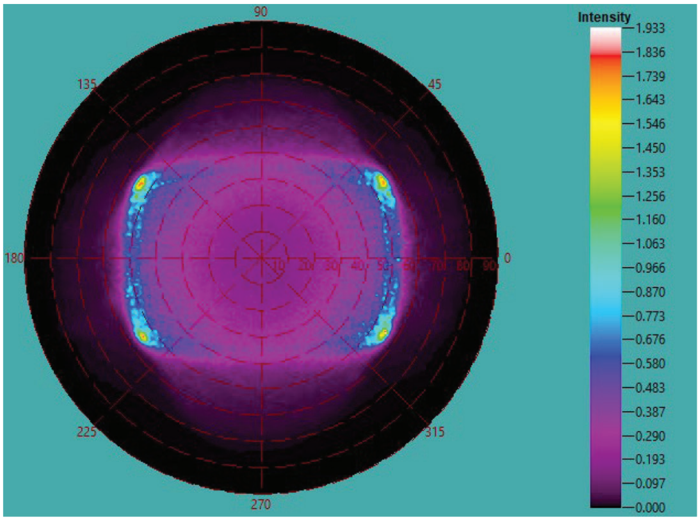
In Figure 8 we show the intensity scatter distribution of an EDR-55x44 polymer-on-glass diffuser measured at a wavelength of 940 nm. It has a horizontal FOV of 44° and a vertical FOV of 55°. The transmission of the diffuser is 92.6% at this wavelength.



EDR-55x44
Transmission 92.6%

Figure 8. Scatter distribution and transmission of an EDR-55x44 diffuser.

Another PoG diffuser is shown in Figure 9 with a FOV of 113° horizontal and 94° vertical. It has a transmission of 92% at a wavelength of 633nm.



EDR-113x94
Transmission 92%

Figure 9. Scatter distribution and transmission of an EDR-113x94 diffuser.

Conclusion

VIAVI Engineered Diffusers are designed to meet an ever-growing range of customer requirements to distribute light in a controlled and efficient manner. Being able to measure the performance of the diffusers is critical to meeting those needs. This article describes the technique for measuring the transmission of the diffusers and describes the factors and properties of the diffusers that can play a role in determining that transmission.

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